AC 2011-462: USING AN ORTHOPAEDIC BIOMECHANICS PROJECT TO REINFORCE SOLID MECHANICS PRINCIPLES

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An orthopaedic biomechanics project to reinforce mechanics principles

Abstract

A team of junior and senior students investigated the mechanics of an interlocked IM rod and tibial Sawbone construct associated with increasing cortical comminution as part of research and design course. Comminution of the cortical bone and its concomitant lack of inherent stability have led to the use of interlocking rods to control length and rotation in unstable fracture patterns. The treatment of long bone fractures with an intramedullary rod has become an accepted practice with surgical techniques and implants being refined over the last 70 years. A clinical question - “what is the clinical significance of fracture comminution and post-operative cortical contact?”, provides a real-world problem for reinforcing the concepts from mechanics of materials. Cyclic axial loading in a nonfailure mode will give results that can be extrapolated for use during the early phases of fracture care when the stability of the limb is being provided solely by the implant. With the results of the tests, the investigators hope to be able to make recommendations for the clinical application of the implants. Evaluation of project by the faculty and project sponsor involved the ability of the students to use mechanics of materials, articulate the design of experiments, testing, analysis through mapping of student tasks and evidence to the ABET a-k objectives.

Introduction

As part of an upper level engineering course involving design and research, students were posed with a clinical question from an orthopaedic surgeon at a collaborating hospital. The nature of orthopaedics readily encompasses engineering principles from core mechanics courses such as statics, dynamics and mechanics of materials or solid mechanics. The proposed clinical question - “what is the clinical significance of fracture comminution and post-operative cortical contact?” – clearly relies on concepts from mechanics of materials and allowed for the opportunity of reinforcement and application of these concepts for the students.

In a continuous effort of educational improvement, faculty evaluate projects using ABET a-k objectives^[1], rating the project on a 1-5 scale for meeting the objectives as stated in the department goals and providing supporting evidence. The evidence for achieving the outcomes occurs in many forms such as weekly team meetings, work by students as witnessed by faculty on aspects of the project (i.e. lab machine training or assisting/reviewing calculations in problem-solving), midterm and final presentations, final project report and meetings with constituents (in this case the project sponsor).

This paper begins with a presentation of the orthopaedic problem and various design of experiment aspects and mechanics of materials concepts employed by the students. A brief summary of the project evaluation is discussed. Finally the results and discussion of this assessment, which include mapping, rate and evidence of the student achievement in meeting the a-k objectives are presented.

The Orthopaedics Project

This section provides slightly edited text from the team's project report that are most relevant to this paper regarding mechanics in an orthopaedic project and for assessment of the project work.

Design and Research Problem

Comminuted fractures are bone fractures where entire portions of broken bone are detached from the rest of the bone body. These fractures are typically represented by the Winquist classification, where Grade 0 (Control Group) represents no comminution, Grade 1 represents minimal less than 25%, Grade 2 represents less than 50%, Grade 3 represents approximately 75%, and Grade 4 is a full comminution with no cortical contact.[2] These types of fracture are often difficult to categorize, due to limited x-ray views and variable nature and severity of trauma.

The current level of care for a comminuted fracture in a long bone is the implantation of an intramedullary, or IM, rod. By using an x-ray of the affected area to properly size an IM rod to the patient, the surgeon drills and reams the shaft of the long bone for the insertion of the rod. The rod is then inserted and fixated typically by one proximal (top) screw and either one or two distal (bottom) screws. The number of distal screws is left to the discretion of the physician and is often associated with the severity of the fracture as well as other factors, such as overall health of the patient, the patient's bone size relative to their weight, the size rod and fixation screw combination used, and whether the bone is osteoporotic. These factors combined with the prospect of the patient resuming activity before the recommended recovery time could lead to improper healing or implant failure. The proposed clinical question by the surgeon and project sponsor is "what is the clinical significance of fracture comminution and post-operative cortical contact?"

In order to provide some guidance to surgeons in answering this question, the mechanics of these fracture situations can be investigated and was the goal of the student project. Specifically, the team was tasked with finding the effects of using a loose or tight fitting IM implant in otherwise identical tibia fracture situations. In order to accomplish this, the team conducted preliminary mechanics analysis of the screw and axial loading of the bone/IM rod construct, developed a fatigue testing protocol, conducted preliminary tests and analyzed results.

Methods (Employed by Team)

Previous studies report that failures of bone/IM rod constructs do not typically occur in the bone, but usually of the fixation screws.[3,4] This failure could be expected because the metal screws would fail due to shear stresses under physiological loading of the bone. Quantifying the amount of shear stress was determined by approximating the screw as a slender beam subject to a 4-point load condition. As an aside project for one of the student's elective courses, a finite element analysis of the bone, rod and screw was also performed to be compared with the analytical solution and determine the stress concentrations. Another important aspect regarding the loading is the amount of load carried by the bone and the rod for the varying levels of comminution. The loads were determined using statically indeterminate axial loading principles. Finally, fatigue testing conditions and the experimental protocol were determined.

The screw was modeled as the beam, and the bone and rod represent the four contact points where force is applied. The free body diagram is shown in Figure 1; the loads due to the rod are P and the loads of the supporting bone are R . The force total load used in the computations was based on the average weight of a male American adult, 176lbs.[5] The shear stress, τ , equals V the shear force and A the cross sectional area of the screw.

$$\tau = V/A \quad (1)$$

Figure 1 – model of screw as 4-point loaded beam

Before experimental testing, the forces and stress in the bone and rod the bone and IM rod setup, it was important to estimate how much force and stress would be applied on the bone and rod when bodyweight was applied. Because of the limited number of samples supplied, the bone samples could not be taken to failure or reach a state of permanent deformation. For this reason, it was necessary to determine if 1x bodyweight was possible to be used as a testing condition. The bone and IM rod implant in a person who is standing or walking can be modeled as an axially loaded, statically indeterminate problem. Using the load-displacement relationship, as well as the fact that the relative displacement between the bone and nail is 0, the following relationships can be developed:

$$F_y = F_B + F_N \quad (2)$$

$$\frac{F_B * L_B}{A_B * (1 - \%) * E_B} = \frac{F_N * L_N}{A_N * (1 - \%) * E_N} \quad (3)$$

$$\sigma_B = \frac{F_B}{A_B}, \sigma_N = \frac{F_N}{A_N} \quad (4)$$

where F is force, L is the length, A is the cross-sectional area, $\%$ is the percent of bone loss, E is the elastic modulus, and σ is the stress. The subscript B represents values of the bone, and the subscript N represents values of the nail. Synthes, the producer of the nail and screws, uses a titanium alloy Ti-6Al-7Nb.[6] Therefore, the elastic modulus used for the nail was 114GPa,[7] and the elastic modulus for the bone was 18.6GPa.[8.9] Due to their complex geometries, the area of the nail was calculated as an area formed by 2 concentric circles, while the area of the bone was calculated approximating it as a triangle. A parametric study was performed where the percentage of bone loss was varied based on the Winquist classification.

Due to the cyclic nature of the testing, fatigue would be the expected form of failure. Because the sample undergoes fluctuating stresses, fatigue can occur at significantly lower stresses than the yield strength of the titanium alloy.[10] An S-N curve shows when fatigue failure will occur at a particular stress for a given number of cycles. An S-N curve was estimated (figure 2) using a method similar to what is called “Four point correlation”.[11]

Figure 2: Estimated S-N curve. The S-N curve represents the low end of the material range as reported by Niinomi^[7], exploring the mechanical properties of the titanium nail.

Design of Experiments (by Team)

A test sample consisted of Sawbone synthetic tibia having a 12 mm canal implanted with IM rods. A set of the bones and rods provided by Syntes were used for the study. The orthopaedic surgeon implanted either an 8mm rod fixed with 4 mm screws or a 11 mm rod with 5 mm screws into the Sawbone tibias. The rod size corresponded to a loose or tight fit, respectively and in both cases there were 1 proximal and 2 distal screws.

The test samples were then potted into PVC end caps with plaster in order to hold the ends of the samples and provide a flat surface for applying a compressive load. The plaster was chosen to serve as the material to hold the bones in the end caps due to its quick drying properties, price, and ease of use. After several design iterations for potting, the bone to be potted was clamped into ring clamps. Plaster and water were mixed subsequently poured into the PVC end cap. The bone was then lowered and the end centered into the PVC end cap. The plaster, at its recommended 2:1 plaster to water ratio, quickly became difficult to manipulate once mixed. The team varied the ratio, until determining that a 1.75:1 was manageable to work with, yet maintained strength.

Each sample was placed into a MTS 830 hydraulic universal test machine for compression testing simulating normal human activity. It was researched and decided by the team that the sample would undergo conditions that would simulate approximately five days worth of normal walking activity. This decision was reached after research and time constraints for the test

machine. A similar study was conducted for 500,000 cycles, which approximates 10 weeks of activity.[3] However, at the testing frequency in the study of 8 Hz, each test would take a little over 17 hours to complete, which was too long for the availability of the test machine. Therefore, it was decided to conduct tests of approximately one week; cutting the testing time by an order of magnitude.

A specific number of cycles, 36,000, to be tested was determined using the constructed S-N curve in Figure 2 using a procedure by Weibsmann and material properties for titanium. At this testing condition, the sample would be placed in a range where the screw would experience an simulated fatigue from activity of nearly one week, but not enough to theoretically cause failure. The compressive load used was based on an average of 176 lb for a full grown male. Accelerated testing at a frequency of 10 Hz was considered first. Due to backing out of screws from apparent resonance of the system, a frequency of 8 Hz was used, which was allow used in a similar study.[3] Peak load and displacement data were collected. Preliminary case study tests were conducted for the case of 2 screws for each of the fracture grades of each of the nail sizes.

Results and Discussion (by Team)

For the 5mm screw (11mm nail) and 4mm screw (8mm nail), the shear stresses were 19.90 MPa and 31.10 MPa, respectively for 785 N of force. These values are an overestimate for the case of 2 distal screws, but for all cases, the shear stress due to static load is well below the shear strength for titanium of 550 MPa.

Statically indeterminate analysis used to determine the force carried by the bone and rod subject to a total static load of 785 N on the bone/rod sample and the corresponding stresses. These are summarized in Table 1 and 2 for each grade and rod. As expected, under the control condition of full cortical contact, load is distributed between the bone and rod. As the bone loss increases (increasing grade) more load is carried by the rod, until at grade 4 the rod supports the entire load.

Table 1: Force and stress of bone and nail for 8 mm nail at various grades

Grade	Diameter, [m]	Force bone, [N]	Force nail, [N]	StressN, [Pa]	StressB,[Pa]
Control	0.008	580.5	203.5	1.09E+07	1.79E+06
1	0.008	534.3	249.7	1.34E+07	2.19E+06
2	0.008	460.9	323.1	1.74E+07	2.84E+06
3	0.008	326.4	457.6	2.46E+07	4.02E+06
4	0.008	0	784	4.22E+07	0.00E+00

Table 2: Force and stress of bone and nail for 11 mm nail at various grades

Grade	Diameter, [m]	Force bone,[N]	Force nail, [N]	StressN, [Pa]	StressB,[Pa]
Control	0.011	328.7	455.3	7.19E+06	1.17E+06
1	0.011	275.4	508.6	8.03E+06	1.31E+06
2	0.011	207.9	576.1	9.09E+06	1.48E+06
3	0.011	119.9	664.1	1.05E+07	1.71E+06
4	0.011	0	784	1.24E+07	0.00E+00

After 20-30 cycles of testing, the MTS machine was able to control loading of the sample between zero and 785 N, which was verified by the recorded force data. The team plotted the differential displacement (the difference between the max and min of each cycle) as the y-axis and the cycle number as the x-axis in the figures 6 and 7 for one sample of each of the 2 rods.

Figure 6: Change in displacement vs. Cycles for 8mm nail at each grade

Figure 7: Change in displacement vs. Cycles for 11 mm nail at each grade

For the 11mm nail (Figure 7), the magnitude of dD increases as the grade of fracture increases. The individual dD tends to decrease slightly or stay constant over the cycle range. The dD lines follow an exponential curve for the first 20,000 cycles, and then follow a linear trend for the duration of the cycles. Logically, as the system becomes less stable (more bone fracture) the IM nailing system should show more displacement between peaks and valleys. This is also suggested by the results of the statically indeterminate cases, where it was shown that forces on the nail increase as grade of fracture increase, which may explain the dD vs. cycle trend for the 11mm nail. The magnitude of the 8mm nail dD shows no correlation or trends yet known. The magnitudes of dD in ascending order are Grade 1, Grade 3, control, Grade 4, and Grade 2. The data follow an exponential curve followed by a linear curve similar to the 11 mm nail.

Assessment methodology for student design/research project

Assessment consisted of determining which of the ABET outcomes were met by the students working on the project and to what extended. The evidence for achieving the outcomes was collected by the instructor through weekly update meetings with the team, working directly with the student on aspects of the project (such as lab machine training or calculations in problem-solving), midterm and final presentations, and the final project report. The evidence was mapped to the goals and ABET a-k and placed in a table along with a 1-5 Likert scale rating. Reinforcement of mechanics principles was of particular importance.

Assessment results and discussion

Table 3 contains the department goals stated to include the ABET a-k objectives along with additional objectives set forth by the American Society of Mechanical Engineers and the department faculty, the student outcome, a 1-5 rating where 1 is low and 5 is high and examples of evidence specific to this project.

As shown in the table as well as the written text from the student project report sections presented earlier in this paper, the team met all of the objectives at a minimum level of slightly above average at 3.5 out of 5 and truly excelled in most with either a rating of 4 or 5 out of 5. It is important to note that in Goal 1, Objective 1, which contains several objectives (a, b, e, and k), and Goal 5, Objective 2 (h) the evidence includes the ability of students to apply concepts from mechanics in order to meet both the technical aspects of the project as well as recognize the relation of mechanics to socially relevant problems. Further, all objectives a-k are met in this project, which provides support for design and research projects providing a great breadth of experience and synthesis on the part of the students. Since this is only the first semester of the project, next steps for the student team include further analysis of data and testing more samples.

Also regarding other evidence of the mechanics capabilities of the students, the instructor was pleased with the various concepts that students may not have used for one to two years, such as recognizing the screw as a beam in 4-point bending and solving this both analytically and computationally. In other cases, the project provided an opportunity to review and reinforce mechanics concepts and faculty to provide assistance in analysis as in the case of the statically indeterminate axial loading problem.

Conclusion

An orthopaedic biomechanics project provided the experience for students to reinforce and apply mechanics principle. The project was discussed, primarily from the student perspective through edited excerpts of the team final report. An assessment was conducted to determine the level of student ability and the evidence of student performance for application of mechanics principles as well as the broader objectives a-k. The students performed well on all mechanics aspects and well above average across the other goals and objectives.

References

1. www.abet.org
2. Wheelless, CR. "Winquist Classification of Femoral Shaft Frx - Wheelless' Textbook of Orthopaedics." *Wheelless' Textbook of Orthopaedics*. Duke Orthopedics. Web. 22 Sept. 2010
3. Brumback, RJ, TR Toal, VP Novak, SM Belkoff, and MS Murphy-Zane. "Immediate Weight-Bearing After Treatment of a Comminuted Fracture of the Femoral Shaft with a Statically Locked Intramedullary Nail." *The Journal of Bone & Joint Surgery* 44th ser. 81.1538 (1999)
4. Bong, MR, FJ Kummer, KJ Koval, and KA. Egol. "Intramedullary Nailing of the Lower Extremity: Biomechanics and Biology." *J. of the American Academy of Orthopedic Surgeons* 15.2 (2007).
5. "FASTSTATS - Body Measurements." *Centers for Disease Control and Prevention*. Web. 19 Oct. 2010.
6. "4.0 Mm and 5.0 Mm Titanium Locking Screws for Synthes Intramedullary Nails." *Synthes*. 2001. Web. 15 Nov. 2010.
7. Niinomi, M. "Mechanical Properties of Biomedical Titanium Alloys." *Materials Science and Engineering* (1998): 231-36.
8. Cuppone, M, BB. Seedhom, E Berry, and E Ostell. "The Longitudinal Young's Modulus of Cortical Bone in the Midshaft of Human Femur and Its Correlation with CT Scanning Data." *Calcified Tissue International* 74.3 (2003): 302-09.
9. Rho, JY, RB. Ashman, and CH Turner. "Young's Modulus of Trabecular and Cortical Bone Material: Ultrasonic and Microtensile Measurements." *Journal of Biomechanics* 26.2 (1993): 111-19.
10. "Fatigue." Web. 4 Nov. 2010. <<http://materialrulz.weebly.com/uploads/7/9/5/1/795167/fatigue.pdf>>.
11. Weihsman, Peter R. *Fatigue Curves without Testing*. Cleveland: Reliable Electric Research Center, 1980. 52-54.

Table 3 – Objectives, student outcomes and evidence for student orthopaedic project

		Address	Evidence
		1-poor 5-well	
Goal 1, Objective 1 - ME graduates will possess the ability to apply knowledge of mathematics, science and engineering (Obj. A) to problem solve (Obj. E), as well as the ability to use the techniques, skills and modern engineering tools necessary for engineering practice (Obj. K). These include the design and conduct of experiments, as well as the analysis and interpretation of data (Obj. B).	Outcome: Students who complete the ME program at Rowan University will be able to solve problems using mathematics, science, and engineering knowledge	5	Applied solid mechanics principles and calculations for beam bending with 4 point load and statically indeterminate situation for bone and nail construct, as well as fatigue failure theory for cyclic failure of screws. Designed and conducted compression experiments, preliminary analysis of results by using tools such as test machine and sensors to record data.
Goal 1 - Objective 2: ME students will possess the ability to design a system, component, or process in both thermal and mechanical systems to meet desired needs (Obj. C & O)	Outcome: Students who complete the ME program at Rowan University will be able to design a system, component, or process.	3.5	Students designed method and process for potting bone/IM nail
Goal 1 - Objective 3: ME students will possess a knowledge of contemporary issues relevant to Mechanical Engineering (Obj. J).	Outcome: Students who complete the ME program at Rowan University will be knowledgeable of contemporary issues.	4	Students met with sponsor and conducted both literature review and research regarding bioengineering within mechanical engineering. Students wrote a technical impact regarding issues of clinic practice and implications of their work.
Goal 2 - Objective 1: ME graduates will possess the ability to function in multidisciplinary teams (Obj. D).	Outcome: Students who complete the ME program at Rowan University will work effectively in multidisciplinary teams.	4	Team of 3 mechanical engineers (2 junior/1 senior) took turns leading efforts at meetings, worked cohesively as a team by division of labor and meeting together to complete project deliverables, holding each other accountable, and regularly meeting with a surgeon.
Goal 2 - Objective 2: ME students will possess the ability to communicate effectively (Obj. G).	Outcome: Students who complete the ME program at Rowan University will be effective communicators.	4	Students successfully presented work in the form of 2 presentations and final written report, which discussed the clinical question, problem statement, relevant principles and calculations, experimental testing and preliminary results
Goal 3 - Objective 1: ME graduates will possess the ability to think creatively and innovatively (Obj. P).	Outcome: Students who complete the ME program at Rowan University will be bold and creative problem solvers.	4	Team brainstormed solutions for potting fixture for bone, ways to consistently simulate fracture and methods to process data.

Goal 4 - Objective 1: ME graduates will possess a knowledge of chemistry and calculus-based physics with depth in at least one (Obj. L), will be able to apply advanced mathematics through multivariate calculus and differential equations (Obj. M), and be familiar with statistics and linear algebra (Obj. N).	Outcome: Students who complete the ME program at Rowan University will possess broad scientific, mathematical and analytical knowledge.	4	Used physics/statics and applied mathematics to calculate forces, used statistics and reliability. Used linear algebra for equation solving.
Goal 4 - Objective 2: ME graduates will possess the knowledge of engineering tools, hardware and software (Obj. R)	Outcome: Students who complete the ME program at Rowan University will use modern tools, hardware and software in problem solving	5	Students effectively used universal test machine and sensors to conduct experiments; software such as SolidWorks, Cosmos, and EES to draw, conduct finite element analysis and solve systems of equations; and Excel and MATLAB for data processing and analysis.
Goal 5 - Objective 1: ME graduates will possess an understanding of professional and ethical responsibility (Obj. F).	Outcome: Students who complete the ME program at Rowan University will understand the need for professional and ethical responsibility.	4	Were informed and followed professional and ethical protocols regarding medical data, such as x-rays.
Goal 5 - Objective 2: ME graduates will possess the broad education necessary to understand the impact of engineering solutions in a global and societal context (Obj. H).	Outcome: Students who complete the ME program at Rowan University will understand and consider the consequences of engineering solutions on society.	3.5	Students need to apply and synthesis principles from multiple courses (solid mechanics, material science, design) as well as study clinical problems and techniques in order to study a socially relevant problem of long bone fractures and fixation.